Ultra-High Energy Neutrino Fluxes: New Constraints and Implications

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We apply new upper limits on neutrino fluxes and the diffuse extragalactic component of the GeV $\gamma-$ray flux to various scenarios for ultra high energy cosmic rays and neutrinos. As a result we find that extra-galactic top-down sources can not contribute significantly to the observed flux of highest energy cosmic rays. The Z-burst mechanism where ultra-high energy neutrinos produce cosmic rays via interactions with relic neutrinos is practically ruled out if cosmological limits on neutrino mass and clustering apply.

I. INTRODUCTION

High energy neutrino astrophysics is currently very active, in particular experimentally [1]. Neutrino telescopes are reaching sensitivities comparable to theoretical expectations for neutrino fluxes based on their connection to primary cosmic rays and secondary $\gamma-$rays [2]. This is in particular the case for upper limits from AMANDA II [3] in an energy range between $\simeq 10^{14}$ eV and $\simeq 10^{18}$ eV, and from the RICE experiment [4] above 10^{16} eV. The former aims to detect neutrinos by looking for showers and/or tracks from charged leptons produced by charged current reactions of neutrinos in ice, whereas the latter is searching for radio pulses emitted by neutrino induced showers in south polar ice. In addition, based on the non-observation of radio pulses from the Earth's surface expected from neutrinos above $\sim 10^{22}$ eV, the FORTE satellite has established upper limits on their fluxes in this hitherto unexplored territory [5].

In the near future sensitivities will further improve by next generation versions of these techniques. For AMANDA this will be ICECUBE [6] at the South pole and possibly a comparable kilometer scale neutrino telescope in the Mediterranean [7], based on ANTARES [52], NEMO [8], and NESTOR [9]. Improved limits from the radio technique may come from the Antarctic Impulsive Transient Antenna (ANITA) which is a planned long duration balloon mission to detect radio waves from showers induced by neutrinos in the antarctic ice [10].

Next generation experiments for ultra-high energy cosmic rays (UHECR) above $\sim 10^{19}$ eV will also have considerable sensitivity to neutrinos, typically from the near-horizontal air-showers that are produced by them [11]. These projects include the southern site of the Pierre Auger Observatory [12], a combination of a charged particle detector array with fluorescence telescopes for air showers produced by cosmic rays above $\sim 10^{19}$ eV, and the telescope array [13], which may serve as the optical component of the northern Pierre Auger site. There are also plans for space based observatories such as EUSO [14] and OWL [17] of even bigger acceptance.

Finally, there are plans to construct telescopes to detect fluorescence and Čerenkov light from near-horizontal showers produced in mountain targets by neutrinos in the intermediate window of energies between $\sim 10^{15}$ eV and $\sim 10^{19}$ eV [18, 20]. Acoustic detection of neutrino induced interactions is also being considered [21].

In an earlier paper [22] we reviewed fluxes in various scenarios in the context of constraints from current cosmic ray data and upper limits on $\gamma-$ray and neutrino fluxes. Besides the improved neutrino flux limits from AMANDA II, RICE, and FORTE, a possibly lower extragalactic contribution to the diffuse GeV $\gamma-$ray background observed by the EGRET instrument on board the Compton $\gamma-$ray observatory [23, 24, 25] has been pointed out recently. An upper limit on the extragalactic diffuse $\gamma-$ray flux constrains the total amount of electromagnetic (EM) energy injected above $\sim 10^{15}$ eV which cascades down to below the pair production threshold for photons on the cosmic microwave background (CMB) [26, 27]. Since in any scenario involving pion production the EM energy fluence is comparable to the neutrino energy fluence, a change in the constraint on EM energy injection can also influence allowed neutrino fluxes. Furthermore, future $\gamma-$ray detectors such as GLAST [28] will test whether the diffuse extragalactic GeV $\gamma-$ray background is truly diffuse or partly consists of discrete sources that could not be resolved by EGRET. This could further improve the cascade limit.

Motivated by these improved constraints and prospects, and by more detailed information available on neutrino sensitivities of future experiments, in the present paper we reconsider flux predictions in scenarios currently often discussed in the literature. As in Ref. [22], we apply our recently combined propagation codes [29, 30, 31, 32]. Sect. II summarizes the numerical technique used in this paper. In Sect. III we discuss the cosmogenic neutrino flux, i.e. the flux of neutrinos produced as secondaries of extragalactic cosmic rays during propagation, and its dependence on various UHECR source characteristics. In Sect. IV we review neutrino flux predictions in extragalactic top-down scenarios where UHECRs are produced in decays of super-massive

particles continuously released from topological defect relics from the early Universe. If UHECRs are new hadrons, they have to be produced as secondaries of accelerated protons which also gives rise to neutrinos. Their fluxes in these scenarios are reviewed in Sect. V. Sect. VI discusses primary neutrino fluxes required in scenarios where the cosmic rays observed at the highest energies are produced as secondaries from interactions with the relic cosmological neutrino background, often called Z-burst scenario. In Sect. VII we discuss neutrino fluxes from active galactic nuclei (AGN) models. Finally, in Sect. VIII we conclude.

II. NUMERICAL TECHNIQUE

Our simulations use an implicit transport code that evolve the spectra of nucleons, $\gamma-$rays, electrons, electron-, muon-, and tau-neutrinos, and their anti-particles along straight lines. Arbitrary injection spectra and redshift distributions can be specified for the sources and all relevant strong, electromagnetic, and weak interactions have been implemented. For details see Refs. [22, 29, 30, 32]. Our results apply to average large scale extragalactic magnetic fields of the order $B \lesssim 10^{-11}\,$G and a universal radio background between the minimal values consistent with observations [33] and moderately low theoretical estimates from radio source counts [34].

For the neutrinos we assume for simplicity that all three flavors are maximally mixed which for our purposes is an excellent approximation [35, 36] and thus have equal fluxes. For each flavor we sum fluxes of particles and anti-particles.

In the present investigation we parameterize power law injection spectra of either protons (for UHECR sources) or neutrinos (for Z-burst models) per co-moving volume in the following way:

$$\begin{aligned} \phi(E,z) &= f(1+z)^m\, E^{-\alpha}\Theta(E_{\max}-E) \\ & z_{\min} \leq z \leq z_{\max}\,, \end{aligned} \tag{1}$$

where f is the normalization that has to be fitted to the data. The free parameters are the spectral index α, the maximal energy $E_{\max}$, the minimal and maximal redshifts $z_{\min}$, $z_{\max}$, and the redshift evolution index m. The resulting neutrino spectra depend insignificantly on $z_{\min}$ in the range $0 \leq z_{\min} \lesssim 0.1$ where local effects could play a role, and thus we will set $z_{\min} = 0$ in the following.

To obtain the maximal neutrino fluxes for a given set of values for all these parameters , we determine the maximal normalization f in Eq. (1) by demanding that both the accompanying nucleon and $\gamma-$ray fluxes are below the observed cosmic ray spectrum and the diffuse $\gamma-$ray background observed by EGRET, respectively.

III. THE COSMOGENIC NEUTRINO FLUX

The flux of "cosmogenic" neutrinos is created by decaying charged pions produced in interactions of primary nucleons of energy above $\simeq 5\times10^{19}\,$eV with CMB photons, the Greisen-Zatsepin-Kuzmin (GZK) effect [37]. This flux depends on the production rate of the primary nucleons which we parameterize according to Eq. (1).

A. Dependence on diffuse photon background

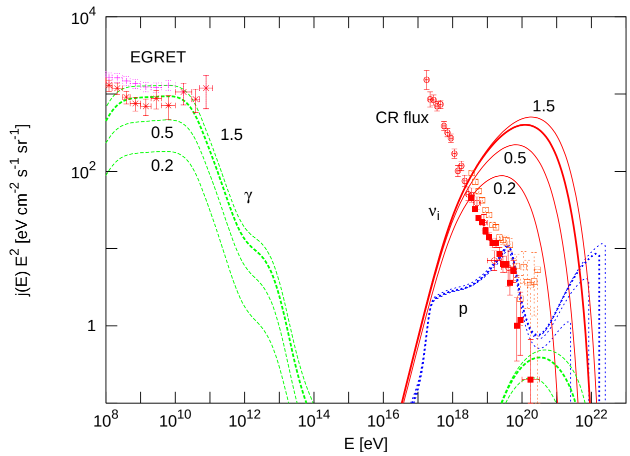

FIG. 1: Dependence of the average cosmogenic neutrino flux per flavor (labeled "ν_i") on the contribution of the accompanying photon flux (labeled "γ") to the old (upper error bars on the left) and new (lower error bars on the left) diffuse EGRET flux estimate. The proton primary parameters in Eq. (1) have been fixed to $m = 3$, $z_{\max} = 2$, and $\alpha = 1$, whereas $E_{\max}$ was varied. The UHECR proton flux (labeled "p") is normalized to the data of the AGASA [38] and HiRes [39] experiments. The numbers indicate the fraction of the new EGRET estimate of the extragalactic diffuse $\gamma-$ray flux contributed by the respective scenario, where the unlabeled thick curves correspond to 100%.

We first consider the dependence of the cosmogenic neutrino flux on the contribution of the accompanying photons to the diffuse $\gamma-$ray flux in the 100MeV - 100 GeV region. As an example, we do this by fixing $m = 3$, $z_{\max} = 2$, and $\alpha = 1$ in Eq. (1), while varying the maximal energy $E_{\max}$. The relatively hard proton spectrum in this scenario could be produced, for example, by acceleration in potential drops or reconnection [40]. We normalize the resulting UHECR flux to the observations above $10^{19}\,$eV and note that the discrepancy between the AGASA [38] and HiRes [39] fluxes above $\simeq 10^{20}\,$eV has a negligible influence on the predicted cosmogenic neutrino flux. As Fig. 1 shows, a decrease of the diffuse photon flux results from a decrease of $E_{\max}$ in this case. The old EGRET flux estimate [23] corresponds to $E_{\max} = 3\times10^{22}\,$eV, whereas the $\simeq 50\%$ smaller new EGRET flux [24] corresponds to $E_{\max} = 2\times10^{22}\,$eV. Most likely

only a fraction of the measured diffuse photon background is connected to GZK neutrinos. In the present scenario 0.5 and 0.2 of the flux measured by EGRET corresponds to $E_{\rm max} = 10^{22}$ eV and $E_{\rm max} = 3 \times 10^{21}$ eV, respectively. Note that the UHECR proton flux is the same in all cases, except for the highest not yet observed energies where the flux can be affected by the distance to the nearest sources.

The cosmogenic neutrino flux has recently been re-evaluated also in Ref. [41] where the EGRET constraint has not been taken into account. The latter, however, eliminates a considerable part of the higher fluxes considered there.

B. Comparison with experimental limits and future sensitivities

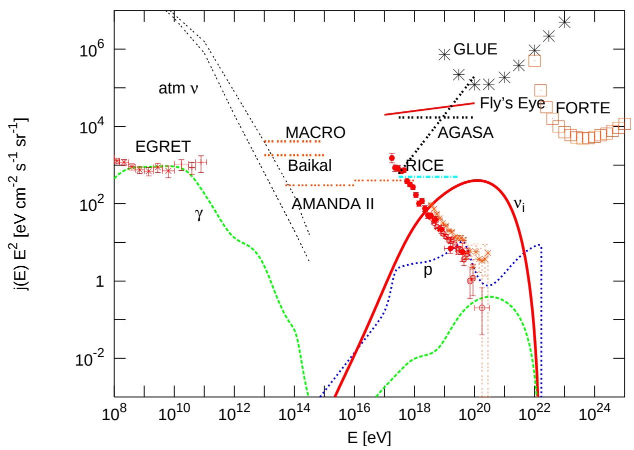

FIG. 2: A scenario with maximal cosmogenic neutrino fluxes per flavor as obtained by tuning the parameters of the proton primaries in Eq. (1) to $z_{\rm max} = 2$, $E_{\rm max} = 2 \times 10^{22}$ eV, $m = 3$, $\alpha = 1$. Also shown are predicted and observed cosmic ray and $\gamma-$ray fluxes, the atmospheric neutrino flux [42], as well as existing upper limits on the diffuse neutrino fluxes from MACRO [43], AMANDA II [3], BAIKAL [44], AGASA [45], the Fly's Eye [46] and RICE [4] experiments, and the limits obtained with the Goldstone radio telescope (GLUE) [48] and the FORTE satellite [5], as indicated. The cosmic ray data are as in Fig. 1, whereas only the new EGRET flux is shown to the left.

The two major categories of experiments are based on detection in water, ice or underground, typically sensitive below $\simeq 10^{16}$ eV, and on air shower detection, usually sensitive at higher energies. Existing neutrino flux upper limits come from the underground MACRO experiment [43] at Gran Sasso, AMANDA II [3] in the South Pole ice, and the Lake BAIKAL neutrino telescope [44] in the first category, and the AGASA ground array [45], the former fluorescence experiment Fly's Eye [46], the Radio Ice Čerenkov Experiment RICE [4] (there is also a limit from the HiRes experiment [49] which is between the RICE and AGASA limits), the

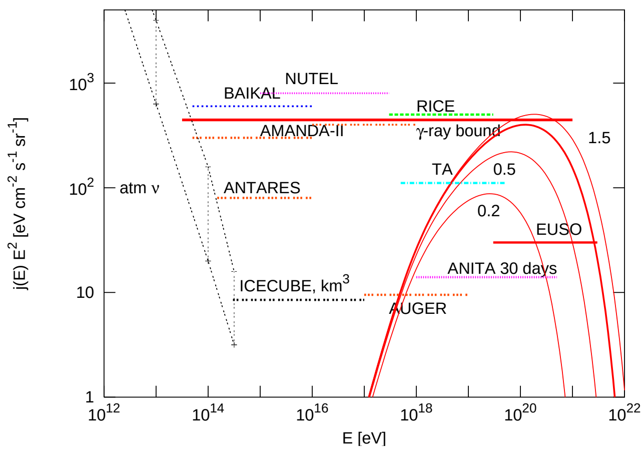

FIG. 3: The cosmogenic neutrino flux per flavor shown in Fig. 1 in comparison with expected sensitivities of the currently being constructed Pierre Auger project to tau-neutrinos [11], the planned projects telescope array (TA) [50], the fluorescence/Čerenkov detector NUTEL [20], the space based EUSO [51], the water-based Baikal [44] and ANTARES [52] (the NESTOR sensitivity for 1 tower would be similar to AMANDA-II and for 7 towers similar to ANTARES [9]), the ice-based AMANDA-II [3] and ICECUBE [6] (similar to the intended Mediterranean km^3 project [7]), and the radio detectors RICE [54] and ANITA [10], as indicated. All sensitivities except for ANITA and RICE refer to one year running time. For comparison, the $\gamma-$ray bound derived from the EGRET GeV $\gamma-$ray flux [24] is also shown.

Goldstone Lunar Ultra-high energy neutrino experiment GLUE [48], and the Fast On-orbit Recording of Transient Events (FORTE) satellite [5] in the second category. As an example, an optimistic cosmogenic neutrino flux is compared with current neutrino flux upper limits in Fig. 2. Future experiments in the first category include NT200+ at Lake Baikal [44], ANTARES [52], NESTOR in Greece [9], as well as a possible common km^3 scale detector in the Mediterranean [7, 8], and ICECUBE [6], the next-generation version of AMANDA at the South pole. The air shower based category includes the Pierre Auger project [11], the telescope array [50], the fluorescence/Čerenkov detector NUTEL [20], and the space based EUSO [51] and OWL [55] experiments. The EUSO sensitivity estimate used here is based on deeply penetrating atmospheric showers induced by electron or muon-neutrinos only [51] and may thus be considerably better if tau neutrinos, Čerenkov events, and Earth skimming events are taken into account [56], for which there are no final estimates available yet. The same applies to the OWL project [55]. The cosmogenic neutrino flux models shown in Fig. 1 are compared with future sensitivities in Fig. 3.

The fluxes shown in Figs. 3 and 4 are considerably higher than the ones discussed in Refs. [57, 58, 59, 60, 61], and should be easily detectable by at least some of these future instruments, as demonstrated by the expected

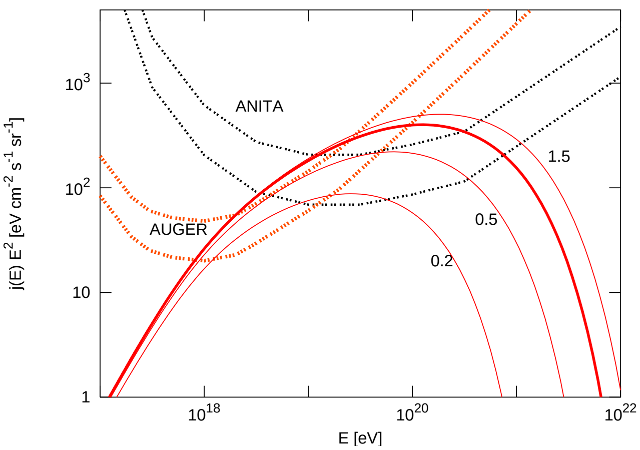

FIG. 4: The cosmogenic neutrino flux average per flavor as shown in Fig. 1 in comparison with differential sensitivities expected for 2006 for the Pierre Auger project [11] (for two years of data taking, assuming strong (upper curve) and no (lower curve) deep inelastic tau lepton scattering) and the ANITA project [10] for 10 (upper curve) and 30 (lower curve) days of observation. The corresponding number of events expected are listed in Tab. I.

Experiment	$F_\nu(1.0)$	$F_\nu(1.5)$	$F_\nu(0.5)$	$F_\nu(0.2)$
2 year Pierre Auger min	4.5	4.8	3.2	1.8
2 year Pierre Auger max	13.4	14.5	9.6	5.4
10 days ANITA	5.0	5.8	2.9	1.3
30 days ANITA	14.9	17.5	8.7	3.8

TABLE I: The number of tau neutrino (Pierre Auger) and electron neutrino (ANITA) events expected to be measured by 2006 for the four neutrino fluxes shown in Figs. 3 and 4. The Pierre Auger differential sensitivity shown assumes two years of data taking until 2006. The minimal (upper line in Fig. 4) and maximal (lower line in Fig. 4) sensitivity depends on the assumptions made for the strength of deep inelastic scattering of tau leptons. For ANITA the case for balloon flights of 10 and 30 days are shown.

number of events listed in Tab. I.

We note that the non-observation of GZK neutrinos in 2006 will significantly restrict the accompanying photon contribution to the EGRET diffuse flux.

IV. NEUTRINO FLUXES IN TOP-DOWN SCENARIOS

Historically, top-down (TD) scenarios were proposed as an alternative to acceleration scenarios to explain the huge energies up to 3×10^{20} eV observed in the cosmic ray spectrum [62]. In these top-down scenarios UHECRs are the decay products of some super-massive "X" particles of mass $m_X \gg 10^{20}$ eV close to the grand unified scale, and have energies all the way up to $\sim m_X$. Thus, the massive X particles could be meta-stable relics of the early Universe with lifetimes of the order the current age of the Universe or could be released from topological defects that were produced in the early Universe during symmetry-breaking phase transitions predicted by in Grand Unified Theories (GUTs). The X particles typically decay into leptons and quarks. The quarks hadronize, producing jets of hadrons which, together with the decay products of the unstable leptons, result in a large cascade of energetic photons, neutrinos and light leptons with a small fraction of protons and neutrons, some of which contribute to the observed UHECR flux. The resulting injection spectra have been calculated from QCD in various approximations, see Ref. [27] for a review and Ref. [63] for more recent work. In the present work we will use the QCD spectra discussed in Ref. [64] and shown in Fig. 11 of Ref. [22]. For the purposes of the current work this is not expected to make a significant difference as compared to the more accurate fragmentation spectra [65].

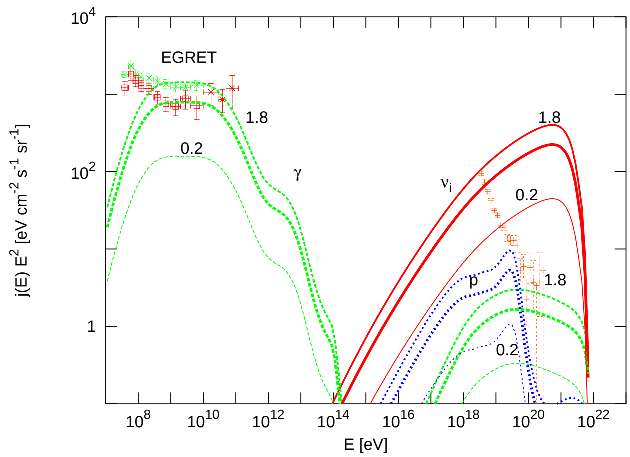

FIG. 5: Flux predictions for a TD model characterized by $p = 1$, $m_X = 2 \times 10^{13}$ GeV. The contribution of photons and protons to the UHECR flux decreases with decreasing fractional contribution to the diffuse photon flux at EGRET energies which is denoted in numbers. Even a TD contribution to the present estimate of the diffuse EGRET flux as high as 100% (unlabeled thick curves) is only marginally consistent with the AGASA UHECR excess. The line key is the same as in Fig. 1.

For dimensional reasons the spatially averaged X particle injection rate can only depend on the mass scale m_X and on cosmic time t in the combination

$$\dot{n}_X(t) = \kappa m_X^p t^{-4+p} , \quad (2)$$

where κ and p are dimensionless constants whose value depend on the specific top-down scenario [62]. Extragalactic topological defect sources usually predict $p = 1$, whereas decaying super-heavy dark matter (SHDM) [66, 67] of lifetime much larger than the age of the Universe corresponds to $p = 2$ [27]. It has also been suggested that annihilation of SHDM particles instead of their decay might contribute to the observed UHECRs [68].

In the SHDM scenario the observable UHECR flux will be dominated by the decay or annihilation products of SHDM in the Galactic halo and thus by sources at distances smaller than all relevant interaction lengths. Composition and spectra will thus be directly given by the injection spectra which are dominated by photons. This is most likely inconsistent with upper limits on the ultra-high energy (UHE) photon fraction above 10^{19} eV [69]. However, requiring that this scenario explains only UHECRs above 4×10^{19} eV allows to avoid this problem [70].

A more severe problem of the SHDM scenario is the spatial anisotropy of the expected signal predicted due to the non-central position of the Sun in our Galaxy [71]. In a recent paper [70] it was shown that the non-observation of anisotropy in the data of the SUGAR experiment excludes any SHDM scenario at the 5σ level assuming that all events above 4×10^{19} eV are from SHDM sources. For the extreme case where SHDM is responsible only for UHECRs above 6×10^{19} eV, the annihilation scenario is disfavored at least at 99% CL by the SUGAR data, while decaying SHDM still has a probability of $\sim 10\%$ to be consistent with the SUGAR data.

The SHDM scenario is therefore disfavored by present experimental data and will be finally tested by the Pierre Auger experiment in the near future. We will therefore here focus on topological defect models with $p = 1$.

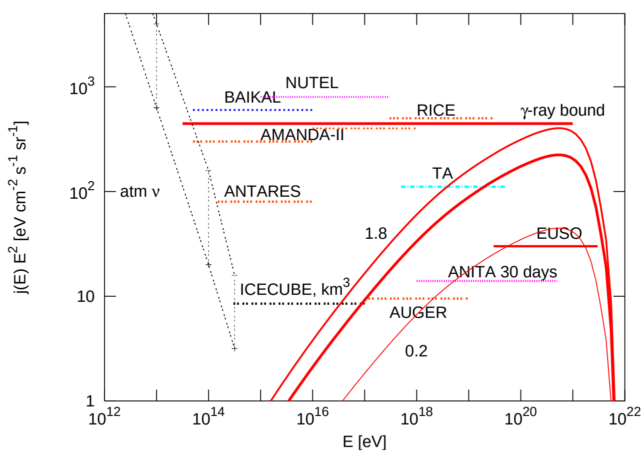

FIG. 6: Neutrino fluxes per flavor predicted by the three normalizations of the TD model of Fig. 5 compared to future experimental sensitivities. The line key is as in Fig. 3.

Fig. 5 shows the results for $m_X = 2 \times 10^{13}$ GeV, with $B = 10^{-12}$ G, and the moderately low theoretical estimate from Ref. [34]. These parameters lead to optimistic neutrino fluxes for the maximal normalization consistent with all data. For detailed earlier discussions of extragalactic top-down fluxes see Refs. [72, 73].

Fig. 5 shows that already the improved upper limit on the true diffuse photon background by EGRET implies too small a UHECR flux compared to the AGASA excess at energies $E \gtrsim 10^{20}$ eV. The parameters used in the figure represent the "best fit point" for this model; in particular for all other masses m_X the disagreement is more severe. The new EGRET upper limit thus strongly disfavors extragalactic top-down scenarios. In addition, independently of this problem of overproduction of GeV $\gamma-$rays, a non-observation of TD neutrinos by 2006 will rule out the possibility that extragalactic top-down mechanisms significantly contribute to the UHECR flux, as can be seen from comparing Fig. 6 with Fig. 5.

V. NEUTRINO FLUX IN SCENARIOS WITH NEW HADRONS AS UHECR PRIMARIES

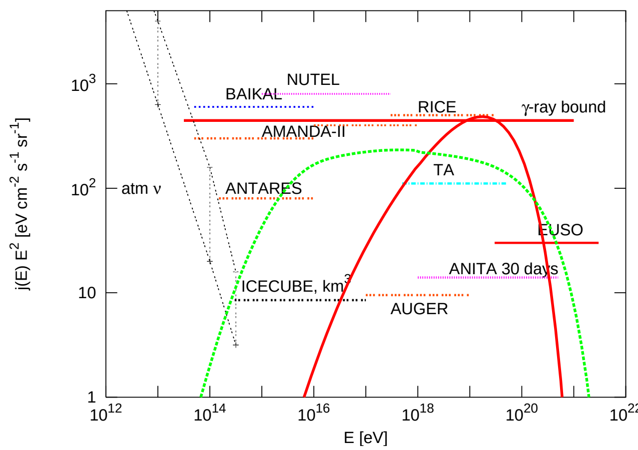

FIG. 7: Neutrino fluxes per flavor predicted by scenarios where UHECRs are explained as new hadrons produced as secondaries of accelerated protons with $m = 3$, $z_{\max} = 2$, compared to expected experimental sensitivities. The solid line is for a flux of primary protons peaked at $E = 10^{21}$ eV and the dashed line is for a primary proton flux $\propto E^{-2}$ up to $E_{\max} = 10^{22}$ eV. The line key is as in Fig. 3.

Supersymmetric (SUSY) models with a strongly interacting particle as lightest supersymmetric particle (LSP) or next-to-lightest SUSY particle (NLSP) are very interesting for explaining the AGASA excess above the GZK cutoff. Hadrons containing a gluino were first suggested by Farrar as UHECR primaries [74, 75]. This model with a light gluino together with a light photino as cold dark matter candidate is meanwhile excluded [76, 77]. However, more general models with a light gluino or a light sbottom quark are still viable.

In a recent paper [78] a model-independent, purely phenomenological approach was developed. Since the observed extensive air showers (EAS) are consistent with simulated EAS initiated by protons, any new primary proposed to solve the GZK puzzle has to produce EAS similar to those of protons. Experimentally still allowed are photons as UHECR primaries: at 90% CL, $\sim 30\%$ of UHECRs above $\sim 10^{19}$ eV can be photons [69]. However, the simplest possibility consistent with EAS observations is to require that the new primary is strongly interacting.

The requirements of efficient production in astrophysical accelerators as well as proton-like EAS in the atmosphere ask for a light hadron, $\lesssim 3\,\mathrm{GeV}$, while shifting the GZK cutoff to higher energies results in a lower bound for its mass, $\gtrsim 1.5\,\mathrm{GeV}$ [79]. From these requirements general conditions on the interactions of new UHE primaries were derived. The production of new hadrons in astrophysical objects was investigated in Ref. [78]. It was found that proton-proton collisions in astrophysical accelerators cannot produce sufficiently high fluxes of new primaries without contradicting existing measurements of photon [23] and neutrino fluxes [3, 4, 5]. In contrast, for a light shadron with mass $\lesssim 3\,\mathrm{GeV}$ and the astrophysically more realistic case of UHE proton collisions on optical/infrared background photons there is no contradiction with existing limits. Also, the required initial proton energy is not too extreme, $E \lesssim 10^{21}\,\mathrm{eV}$, which may be achieved by astrophysical acceleration mechanisms. The only essential condition for the sources is that they should be optically thick for protons in order to produce these new hadrons. This condition applies to all models with new particles produced by protons.

One of the important features of scenarios with new hadrons, and of any model in which the production cross section $\sigma_{p\gamma\to S}$ of a new particle S is much smaller than the total proton-photon cross section $\sigma_{p\gamma}$, is the high flux predicted for secondary high-energy neutrinos. This neutrino flux is approximately $F_{\rm CR}\sigma_{p\gamma}/\sigma_{p\gamma\to S}$ in terms of the maximal contribution of S particles to the observed cosmic ray flux, $F_{\rm CR} \simeq (E/10^{20}\,\mathrm{eV})^{-2}$ eV/(cm^2 s sr).

Fig. 7 shows that for a primary proton flux $\propto E^{-2}$, this model can be restricted already with 3 years of AMANDA-II data. A non-observation of neutrinos by 2006 will make it impossible to render the production cross section of the new hadrons consistent with existing limits in these scenarios.

VI. THE Z-BURST SCENARIO

In the Z-burst scenario UHECRs are produced by Z-bosons decaying within the distance relevant for the GZK effect. These Z-bosons are in turn produced by UHE neutrinos interacting with the relic neutrino background [80]. If the relic neutrinos have a mass m_ν, Z-bosons can be resonantly produced by UHE neutrinos of energy $E_\nu \simeq M_Z^2/(2m_\nu) \simeq 4.2\times10^{21}\,\mathrm{eV}\,(\mathrm{eV}/m_\nu)$. The required neutrino beams could be produced as secondaries of protons accelerated in high-redshift sources. The fluxes predicted in these scenarios have recently been discussed in detail in Refs. [32, 81]. In Fig. 8 we show an optimistic example taken from Ref. [32]. As in Refs. [32, 81] no local neutrino over-density was assumed. The sources are assumed to not emit any $\gamma-$rays, otherwise the Z-burst model with acceleration sources overproduces the diffuse GeV $\gamma-$ray background [32]. We note that no known astrophysical accelerator exists that meets the requirements of the Z-burst model [32, 82].

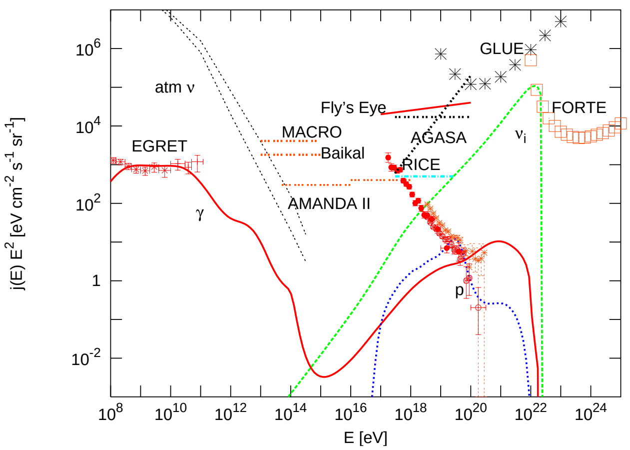

FIG. 8: Flux predictions for a Z-burst model averaged over flavors and characterized by the injection parameters $z_{\rm min} = 0$, $z_{\rm max} = 3$, $\alpha = 1$, $m = 0$, $E_{\rm max} = 3\times10^{22}$ eV in Eq. (1) for neutrino primaries. The sources are assumed to be exclusive neutrino emitters. All neutrino masses were assumed equal with $m_\nu = 0.33$ eV and we again assumed maximal mixing between all flavors. The line key is as in Fig. 2.

However, a combination of new constraints allows to rule out the Z-burst mechanism even for pure neutrino emitting sources: A combination of cosmological data including the WMAP experiment limit the sum of the masses of active neutrinos to $\lesssim 1\,\mathrm{eV}$ [83]. Solar and atmospheric neutrino oscillations indicate that individual neutrino masses are nearly degenerate on this scale [36], and thus the neutrino mass per flavor must satisfy $m_\nu \lesssim 0.33\,\mathrm{eV}$. However, for such masses phase space constraints limit the possible over-density of neutrinos in our Local Group of galaxies to $\lesssim 10$ on a length scale of $\sim 1\,\mathrm{Mpc}$ [84]. Since this is considerably smaller than the relevant UHECR loss lengths, neutrino clustering will not significantly reduce the necessary UHE neutrino flux compared to the case of no clustering. For the maximal possible value of the neutrino mass $m_\nu \simeq 0.33\,\mathrm{eV}$ the neutrino flux required for the Z-burst model is only in marginal conflict with the FORTE upper limit [5], as shown in Fig. 8. For all other cases the conflict is considerably more severe. Also note that this argument does not depend on the shape of the low energy tail of the primary neutrino spectrum which could thus be even monoenergetic, as could occur in exlusive tree level decays of superheavy particles into neutrinos [85]. However, in addition this possibility has been ruled out by overproduction of GeV $\gamma-$rays due to loop effects in these particle decays [86].

As was discussed in Ref. [32], the Z burst scenario involving normal astrophysical sources producing neutrinos and photons by pion production within the source were already ruled out by the former EGRET limit.

VII. NEUTRINO FLUXES IN SCENARIOS INVOLVING ACTIVE GALACTIC NUCLEI

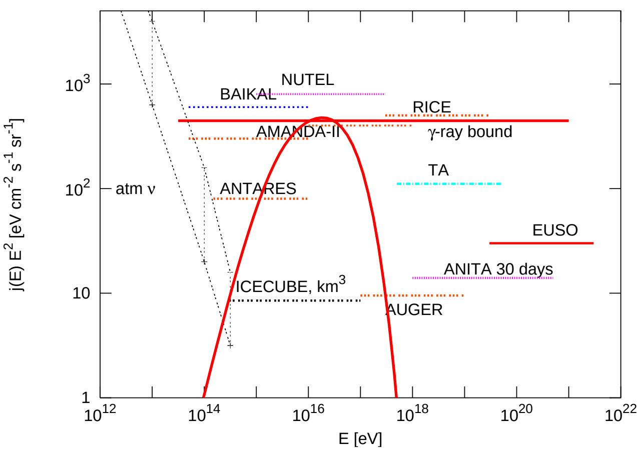

FIG. 9: Neutrino flux per flavor predicted for the AGN model from Ref. [87] for a uniform distribution of blazars (no redshift evolution). The position of the peak is governed by the initial proton distribution. The normalization is determined by the amplitude of the accompanying $\gamma-$ray flux to the new diffuse EGRET flux estimate. The line key is as in Fig. 3.

Active Galactic Nuclei (AGN) are very promising sites of particle acceleration. Though there is no direct evidence of proton acceleration in these objects, according to the Hillas condition $E_{\rm max} \sim qBR$ for the maximal energy, where q is the charge, B is the magnetic field and R is the linear size of the acceleration region, AGN cores, jets or hot spots can be sites for acceleration of UHECRs up to the highest energies $E \sim 10^{19} - 10^{21}$ eV. Once accelerated, protons can escape the AGN freely or can lose part of their energy in interactions with background protons and photons. High energy neutrinos can be produced in AGN via pion production by accelerated protons.

The total power of a given object in neutrinos can be related to the total power in $\gamma-$rays of MeV-GeV energies. However, such a connection is not straightforward because the observed high energy $\gamma-$rays can be produced by several mechanisms not involving neutrino production, for example proton synchrotron radiation in magnetic fields and inverse Compton scattering of MeV-GeV electrons. Moreover, the spectrum of neutrinos from AGN are even more difficult to predict than the spectrum of cosmogenic neutrinos. The reason is that besides the unknown model-dependent spectrum of primary protons, the spectrum of background photons is also not known and in general is model dependent. Also, AGN are divided into subclasses with different properties of the observed photon spectrum. Many of those properties do not directly relate to the possible neutrino spectrum. This means that it is very difficult to predict the space distribution of those AGN which contribute to the neutrino flux from the distribution of AGN subclasses. At least these distributions can be very model dependent.

Due to the above complications we suggest here a phenomenological approach to the prediction of neutrino fluxes. Within this approach the neutrino flux in most of AGN models can be approximately characterized by three parameters, namely the amplitude, width and position of the peak (plateau) in the differential spectrum. The position of the peak (plateau) is related to the spectrum of background photons. The combination of amplitude and width defines the total power in neutrinos which can be related to the total power in MeV-GeV photons produced in the same pion production reactions. Experimental bounds on neutrino fluxes can be converted to constraints on model parameters.

A similar approach can be used for most existing models which predict neutrino fluxes from AGN, see for example Ref. [88]. The only difference would be the connection of the phenomenological parameters of the observed neutrino spectrum to the physical AGN parameters in the given model.

As an example, we will use the model of $\gamma-$ray powered jets of Ref. [87]. In this model the high energy γ-rays are produced by accelerated protons interacting with the ambient photon fields (supplied, for example, by the accretion disk around the massive black hole) through photo-meson processes. At the same time those protons produce neutrinos which are emitted in the direction of the jet. Therefore, this model predicts a high neutrino flux comparable in power with the γ-ray flux. The detailed numerical simulations of proton acceleration in the central engine of the AGN [89] show that the collimated jet of almost mono-energetic high energy protons (linear accelerator) can be created in the electro-magnetic field around the black hole and the energy of those protons can be converted into photons and neutrinos, while protons can be captured inside the source. The nucleon flux leaving the AGN is well below the observed cosmic ray flux in this scenario. Furthermore, since all nucleons leaving the source are well below the GZK cutoff, there is no cosmogenic contribution to the neutrino flux from these sources.

Fig. 9 shows a typical prediction for the diffuse neutrino flux in this model. The neutrino flux is maximized in such a way that the accompanying photon flux saturates the new EGRET bound. As seen from Fig. 9, already now AMANDA-II and RICE data start to restrict AGN models. Three years of AMANDA-II data will significantly restrict the parameter space of those models. This will also restrict the contribution of π^0 production in AGN to the extragalactic diffuse $\gamma-$ray flux at EGRET energies.

In the AGN model discussed above, blazars would be seen by neutrino telescopes as point-like sources with neutrino fluxes which are smaller or of the same order as the photon flux emitted by these same sources and which are detectable by γ-ray telescopes. The most probable sources were discussed in Ref. [90].

VIII. CONCLUSIONS

Based on our transport code we reconsidered neutrino flux predictions and especially their maxima consistent with all current data on cosmic rays and updated upper limits on neutrino fluxes and the diffuse extragalactic GeV $\gamma-$ray background. We discussed predictions for fluxes of cosmogenic neutrinos produced through pion production of UHECRs during propagation, and for fluxes produced by AGN. We showed that extragalactic top-down scenarios can not contribute significantly to the observed ultra-high energy cosmic ray flux if standard evolution histories and injection spectra are used. The Z-burst mechanism where ultra-high energy neutrinos produce cosmic rays via interactions with relic neutrinos is ruled out except if cosmological neutrino mass limits are invalid and/or if relic neutrinos cluster more strongly than expected based on standard phase space principles. Only the case of maximal neutrino mass $m_\nu \simeq 0.33\,\mathrm{eV}$ consistent with large scale structure and CMB observations is only moderately excluded.

The fact that a good part of the speculative scenarios of UHECR origin are now ruled out makes the enigma of the highest energy particles an even more exciting subject of study in our opinion.

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